Transistor and Amplifier Modeling Methods for Microwave Design

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I would like to acknowledge various contributions and collaborations:

- Rick Connick, Byoungyong Lee, Dr. Jiang Liu, Modelithics, Inc.
- Bill Clausen, formerly with Modelithics (now with RFMD)
- Dr. W.R. Curtice, W.R. Curtice Consulting
- Dr. David Snider, Univ. South Florida
- Ray Pengelly and Simon Wood, Cree, Inc.
- Dr. Steve Maas, Non-linear Technologies, Inc.
- Dr. Peter Aaen, Freescale
- Dr. Yusuke Tajima, Auriga Measurement Systems
Overview

- Nonlinear Modeling
- Thermal and Trap Issues
- MESFET and PHEMT Modeling
- MOSFET Modeling
- HBT Modeling
- Behavioral Modeling of Amplifiers
- References
Motivation/Need for Non-Linear Models for PA Design

- The demand of accurate models
  - Accurate models can predict precisely the performances of RF circuit designs – yet challenges remain!
  - PA Design has become more complex in terms of competing multi-dimensional requirements of BW, efficiency, linearity and power performance.
- Electro-thermal effects often a critical issue for accurate HPA modeling
- Requirement of Isothermal measurements
  - Self-heating effects held constant
  - Some applications (GSM, radar) required pulsed operation.
- Advance model testing
  - Wireless systems use various digital modulation signals.
  - Are currently available models adequate for emerging requirements?
Nonlinear Modeling

- Device behavior is different under large-signal conditions than for small-signal conditions.
Source of PA Nonlinearities

Example BJT Device
Basic Nonlinearities of PAs

- Frequency generation
- Intermodulation
- AM-AM and AM-PM conversion
- Spectral spreading
NL Transistor Modeling Process

Characterizations
- static/pulse IV, CV, S-parameter

Appropriate Model
- (Angelov, EEHMT CFET, etc.)

Parameter Extraction
- (IC-CAP, ADS, etc.)

Model Validation

Optimization / Tuning

Advance testing
- Load pull
- Pulse RF measurements
- Time domain
- Digital modulation

Acceptable Model
• Accurate simulation and measurements are required.
• Shell representation of packaged entire transistor.

Used with permission from Peter Aaen of Freescale
Inside an RF Power Transistor

This packaged transistor operates at 2.1 GHz and is capable of producing 170 W (CW) output power.

*Used with permission from Peter Aaen of Freescale*
Test Configuration for NL Transistor Model Development

- Bias tee
- DUT (InGaP HBT)
- RF Wafer Probe Station
- Bias force
- Bias force sense
- Anritsu 37369C VNA
- Keithley 4200 DC Parameter Analyzer
- GPIB connection
- Agilent ICCAP
- Pulsed IV Analyzer
- Bias Etee
- Bias Etee sense
- Bias force sense
- RFE Wafer Probe Station
Extraction of $I_D$ Equation

The quality of the IV extraction plays a large part in determining the path of the large-signal swing in the IV plane as well as gain and output conductance.
80 W MESFET

Model Representation

Test Layout

Legend
- Model
- Measured

Vds (V)

Dimensions in mils

PRECISION MEASUREMENTS AND MODELS YOU TRUST
Mextram Model for InGaP HBT
Mextram Model for InGaP HBT

Measured (blue) and Modeled (red) S-parameters

$ib = 50 \sim 200\mu A$ in a step of 50uA and $vce = 3V$. The frequency range is from 0.5 to 20 GHz with the ambient temperature 25°C.
Test Configuration for NL Transistor Model Validation

Note: Can also be performed under pulsed RF conditions with minor modifications to setup.
80 W MESFET

1850 MHz loadpull results (Source = 13.5-j25.0 Ohms)

<table>
<thead>
<tr>
<th>Device</th>
<th>Pout</th>
<th>Load</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device 1</td>
<td>45.92</td>
<td>6.6-j18</td>
<td>4.78-j16.2</td>
</tr>
<tr>
<td>Device 2</td>
<td>45.86</td>
<td>6.86-j17.91</td>
<td>4.78-j16.86</td>
</tr>
<tr>
<td>Model</td>
<td>46.08</td>
<td>5.23-j18.04</td>
<td>5.06-j12.5</td>
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</tbody>
</table>
Pulsed Load-Pull – HVVI Device

“MET” Model Developed by Modelithics

Pin = 23dBm, Freq = 1200 MHz, Vds = 28 V, Vgs = 1.65 V. $\Gamma_S = 0.83 < -98$. In measurement pulse width = 200us, pulse separation = 2ms.

Fixed Load Pull
Freq = 1.2000 GHz
TSource: 0.6302 < -36.47
TSource_2nd: 0.9020 < -36.20
TSource_3rd: 0.6693 < 22.78

Pout max = 38.35 dBm
at 0.6902 < -112.57
S contours, 1.00 dBm step
(24.00 to 38.00 dBm)
Specs: OFF
What are the main considerations for non-linear Non-linear transistor models?

- **Overall measurement accuracy**
  - Correct calibration
  - Repeatability
  - De-embedding model
  - RFIV vs. DCIV

- **Suitability of model**
  - equation set (model template) limitations/intent
  - physically meaningful parameters?

- **Model testing/validations**
  - Conventional - general
  - Advanced – application specific
Pulsed IV Measurement

- Measurements are performed during brief (~0.2 µs) excursions from a quiescent bias.
- The pulses are usually separated by at least 1 ms.
- Thermal and trap conditions during the measurement are those of the quiescent bias, as in high-frequency operation.
Pulsed IV system AU4550

From Yusuke Tajima, used with permission.

June 16, 2008

2008 IMS Workshop
Why Pulsed IV?

1. Thermal  
2. Field induced traps

Pulsed IV data of a pHEMT at different quiescent conditions

June 16, 2008  
2008 IMS Workshop
Electrothermal “Circuit”

$T_C = Z_{th} P_D + T_A$

$Z_{th} = R_{th} // \left( \frac{1}{j \omega C_{th}} \right)$

$C_{th} = \frac{\tau_{th}}{R_{th}}$

As $\omega \to 0$, $Z_{th} \to R_{th}$

As $\omega \to \text{large}$, $Z_{th} \to 0$
Trapping Effects

- Trapping Effects in MESFETs*:
  - Substrate Traps
  - Surface Traps
- Electron Capture → Fast Process
- Electron Emission → Slow Process

# A Subset of Available FET Model Templates

<table>
<thead>
<tr>
<th>FET models</th>
<th>Number of parameters</th>
<th>Bias dependent capacitance/ Electro-Thermal effect</th>
<th>Original Device Context</th>
</tr>
</thead>
<tbody>
<tr>
<td>JFET [1]</td>
<td>27</td>
<td>No/No</td>
<td>GaAs FET</td>
</tr>
<tr>
<td>Curtice3 [2]</td>
<td>59</td>
<td>Yes/No</td>
<td>GaAs FET</td>
</tr>
<tr>
<td>CFET [3]</td>
<td>48</td>
<td>Yes/Yes</td>
<td>HEMT</td>
</tr>
<tr>
<td>EE HEMT1 [4]</td>
<td>71</td>
<td>Yes/No</td>
<td>HEMT</td>
</tr>
<tr>
<td>Angelov [5]</td>
<td>80</td>
<td>Yes/Yes</td>
<td>HEMT/MESFET</td>
</tr>
<tr>
<td>CMC (Curtice/Modelithics/Cree) [6]</td>
<td>55</td>
<td>Yes/Yes</td>
<td>LD MOSFET</td>
</tr>
<tr>
<td>MET (Motorola Electro-Thermal) [7]</td>
<td>62</td>
<td>Yes/Yes</td>
<td>LD MOSFET</td>
</tr>
<tr>
<td>MOS Level 1/2/3 [1]</td>
<td>40/48/47</td>
<td>Yes/Yes</td>
<td>MOSFET</td>
</tr>
<tr>
<td>BSIM3 (v3.24) [8]</td>
<td>148</td>
<td>Yes/Yes</td>
<td>MOSFET</td>
</tr>
<tr>
<td>BSIMSOI3 [9]</td>
<td>191</td>
<td>Yes/Yes</td>
<td>SOI MOSFET</td>
</tr>
</tbody>
</table>
EEHEMT Large Signal FET Model

- DC and AC behavior separated \(\rightarrow\) simpler extraction
- Temperature effects modeled through equations – not electro-thermal circuit.
Angelov Large-Signal FET Model

- Traditional single-pole electrothermal subcircuit (not shown) accounts for heating effects
- Available in most simulators also in Verilog A
CFET Model Topology

- Developed by Dr. Walter Curtice and used by Modelithics.
- Designed for GaAs/GaN MESFETs and HEMTs.
Non-Linear (EEHEMT) Model for NE 3210 S01

- **IV Fit**
  - Graph showing the IV fit with voltage and current values.

- **S-Parameter Fits**
  - 2V, 20 mA
  - Graphs showing S-parameters at different frequencies and phases.

- **2-Tone IM Results – 8 GHz 2V, 20 mA**
  - Graphs showing 2-tone intercept point results.

- **Power Compression – 8 GHz 2V, 20 mA**
  - Graphs showing power compression results at 8 GHz.
MOSFET Modeling

- Motorola’s Electro-Thermal (MET) Model
- Curtice-Modelithics-Cree (CMC) Model
- Both of these models possess traditional electrothermal subcircuits.
- Used for Si LDMOSFET, VDMOSFET devices
  - No traps
  - Electrothermal subcircuit and temperature dependence extraction are much simpler!
The Curtice-Modelithics-Cree (CMC) model is a proprietary electro-thermal LDMOS model based on work of Fager et.al. (see IEEE Trans. MTT, Dec. 2002)

The model provides accurate predictions of power, efficiency and distortion performance over a wide range of devices sizes.


The CMC model is copyright Cree, Inc. © 2004-2008 all rights reserved.
30 W LDMOS Device Modeling

Graphs showing the characteristics of LDMOS devices.

- **Gate-to-source voltage [V]** vs **Transconductance [S]**
- **Vg (V)** vs **Ids (A)**
- **Gate to source voltage [V]** vs **Drain current [A]**

Sub-threshold, Quad, Linear, and Compression regions are indicated.
LDMOS Model Fit to Pulsed IV Data

CMC Model for 1 W: solid lines, model  pulsed IV data: dashed lines

Setting Thermal Resistance to 0 or Rth value Removes and adds Self-Heating
30 Watt LDMOS Power FET

The CMC model is copyright Cree, Inc. © 2004-2008 all rights reserved.
150W Phillips Power Transistor – Curtice-Modelithics-Cree (CMC) Model

The CMC model is copyright Cree, Inc. © 2004-2008 all rights reserved.
## Available HBT Model (Templates)

<table>
<thead>
<tr>
<th>BJT models</th>
<th>Number of parameters</th>
<th>substrate effect / self heating</th>
<th>Original Device Context</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP (1970)</td>
<td>24</td>
<td>No/No</td>
<td>Si BJT</td>
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<tr>
<td>VBIC (1985)</td>
<td>102</td>
<td>Yes/Yes</td>
<td>SiGe BJT</td>
</tr>
<tr>
<td>Mextram (1987)</td>
<td>81</td>
<td>Yes/Yes</td>
<td>SiGe HBT</td>
</tr>
<tr>
<td>Mextram (1987)</td>
<td>(version 504)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HICUM (1995)</td>
<td>114</td>
<td>Yes/Yes</td>
<td>GaAs HBT</td>
</tr>
<tr>
<td>Agilent (2003)</td>
<td>124</td>
<td>Yes/Yes</td>
<td>InP/GaAs HBT</td>
</tr>
<tr>
<td>FBH (2005)</td>
<td>80</td>
<td>No/Yes</td>
<td>GaAs HBT</td>
</tr>
<tr>
<td>Curtice (2004)</td>
<td>58</td>
<td>No/Yes</td>
<td>GaAs HBT</td>
</tr>
</tbody>
</table>
Mextram Model for 3x20x2 InGaP HBT

5.5 GHz power sweep results at \( v_c = 3V \) and \( i_b = 100\mu A \).
Source reflection coefficient \( G_{ms} = 0.0652 < 148.97 \) (mag<deg); L
Load reflection coefficient \( G_{ml} = 0.0735 < 36.24 \) (mag<deg).
- Constant Base Current vs. Constant Base Voltage -
(See B. Lee, L. Dunleavy, “High Frequency Electronics, May 2007.)

-o- line: Mextram 504 model and solid line: measurements

(a) The case of constant base voltage (Vb=1.33V)

(b) The case of constant base current (Ib=89.4uA)
Behavioral Models

- Empirical models (behavioral models, black-box models)
  - Requires no knowledge about the internals of the PA
  - Based on the observation of the input-output signal relationships
  - Its simulation performance heavily depends on the dataset used for the extraction of the model
  - It fits well to the given datasets and requires small simulation time;
  - However it may suffer when trying to extrapolate the PA performance or fit to different datasets (by that means different PA topologies)

\[
y(t) = k_1 x(t) + k_2 x(t)^2 + k_3 x(t)^3
\]
PA Modeling Techniques

- Circuit Level Models (Physical Models)
  - Based on the knowledge of the amplifiers’ circuit structure
  - Require accurate active device models and other components
  - The simulation results can be accurate, however, time-consuming

Accurate NL device model needed
“Built-in” ADS Amplifier Models

Amplifier AMP1
S21=dbhpolar(0,0)
S11=phpolar(0,0)
S22=phpolar(0,180)
S12=0
NF=
NFmin=
Sopt=
Rn=
Z1=
Z2=
GainCompType=LIST
GainCompFreq=
ReferTolInput=OUTPUT
SOL=
TOL=

Psat=
GainCompSat=5.0 dB
GainCompPower=GainComp=1.0 dB
AM2PM=
PAM2PM=

Freq=1.0 GHz
P2DFile="p2dfile.p2d"
iVar1=iVal1=

AmplifierS2D AMP1
S2DFile="s2dfile.s2d"
SSfreq=auto
InterpMode=Linear
InterpDom=Data Based
“Built-in” AWR Models
Capabilities of Built-in Models

- S-parameter, NPar
- Gain compression
- Phase compression
- TOI, etc
- Can use multiple dimensional datasets, including nonlinear gain compression information vs bias, temperature, frequency, etc
- Can simulate in envelope domain for outputs such as ACPR/Spectral spreading
Frequency-related Memory Effects

Measured results for Murata XM5060 PA sample

Carrier frequency related AM-AM and AM-PM variation
Example Approach for Frequency-related Nonlinear Effects – ADS Amplifier Model

Simple file driven model constructed based on the measured datasets at different frequencies.

Simulated output spectrum shows the correlation between the spectral regrowth and the PA performance at different frequencies.
Combined P2d/S2D Model

AMP_TRI_TGA6399-SCC
AMP_TGA6399_SCC_1
RFfreq=2 GHz
CEFreqSpacing=1 MHz
Bias=5
Lerr=25
sim_mode=0
BWRmove=0
P2D/S2D MMIC example (cont)

Triquint TGA8399B MMIC amplifier, bias of 5V, frequency at 11.25 GHz

Comparison of the measured and simulated Power. Blue is measurement; Red is model result.
Circle for -10C, square for 25C and triangle for 60C.
Large Signal Scattering Function Theory

- Designed to overcome the limitation of the small-signal S-parameter
- Take into account the fundamental tones as well as the harmonics
- The S-parameters become amplitude-dependent
Poly-Harmonic Distortion (PHD) Behavioral Model (Root et al.)

- Recent application of the large-signal scattering function theory includes the “PHD Model” which targets the broad-band amplifiers
- It combines the A11-dependent S and T functions to characterize the Bpk at different port “p” and harmonic index “k”
- It is implemented in ADS using FDD component and DACs

\[
B_{pk}(|A_{11}|, f) = \sum_{q} \sum_{l=1,...,M} S_{pq,kl}(|A_{11}|, f) \cdot P^{k-l} \cdot A_{ql} \\
+ \sum_{q} \sum_{l=1,...,M} T_{pq,kl}(|A_{11}|, f) \cdot P^{k+l} \cdot A^{*}_{ql}
\]

\[T_{p1,k1} = 0.\] (1)

Utilize the large-signal scattering function theory and consider the fundamental tone only, we can get a simplified model equation shown below:

\[
B_2 = S_{21}A_1 + S_{22}A_2 + T_{22}A_2^*
\]

\[
= S_{21}A_{11} + S_{22}B_2\Gamma_L + T_{22}(B_2\Gamma_L)^*
\]

\[
S_{21} = C_1 + jC_2 \\
S_{22} = C_3 + jC_4 \\
T_{22} = C_5 + jC_6
\]

The \( C_n \) (\( n=1 \) to 6) are the model coefficients and should be derived from optimizations

Can be implemented in ADS using FDD component
Derivation of the model

- The advantage of this model is that it depends on readily available load-pull and VNA instruments and more available measurement processes

- Measurements required to derive this model
  - Small signal S-parameters
  - AM-AM loadpull measurement,
  - AM-PM loadpull measurement

Gain and phase compression at 50 ohm (MAX2373 RFIC LNA)

Frequency: 900 MHz
Pin: -30 dBm to 5 dBm
Bias: Vagc, 1.3875 V; Vcc, 2.775 V
Simulated Fund. tone and IM3 at load b

Note: the “Large S21 model” neglects the last conjugate term.
Volterra Modeling for System Simulation

- Volterra methods are based on the idea that a nonlinear transfer characteristic can be expressed as a functional series.

\[
\begin{align*}
    w(t) &= \int_{-\infty}^{\infty} h_1(\tau)s(t-\tau_1)d\tau_1 \\
    &\quad + \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_2(\tau_1, \tau_2)s(t-\tau_1)s(t-\tau_2)d\tau_1 d\tau_2 \\
    &\quad + \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_3(\tau_1, \tau_2, \tau_3)s(t-\tau_1)s(t-\tau_2)s(t-\tau_3)d\tau_1 d\tau_2 d\tau_3 + \ldots
\end{align*}
\]

- The \( h_n \) are \( n \)th order Volterra kernels. \( w(t) \) is the response and \( s(t) \) is the excitation.

- The expression can be viewed as an \( n \)-dimensional convolution integral.

From Dr. Steve Maas, used with permission.
Volterra Model Extraction

The model is extracted from one, two, and three-tone HB analyses of the circuit.

From Dr. Steve Maas, used with permission.
From Dr. Steve Maas, used with permission.
Summary

- Non-linear device measurement/modeling requires...
  - Careful attention to measurement setup/accuracy
  - Pulsed multi-temperature testing
  - High current/high power instrumentation and components
  - Advanced non-linear instrumentation (e.g. load-pull)
- Large signal modeling requires
  - Advanced models (templates) and extraction techniques.
  - Focused expertise that can pull together the varied aspects of IV, S-parameter and non-linear test results into an effective modeling extraction and validation.
- A measurement/modeling team is best!
Summary (cont’d)

- A Good Behavioral Model…
  - Needs be created based on measurement datasets through instruments available to the modelers.
  - Good News! More advanced non-linear test instruments/software are becoming available.
  - Model should be easy to use and no more complex than necessary.
  - Powerful enough to present multiple dimensional datasets for designers to inspect the amplifier’s performance in a system view
  - (Ideally) Model should be supported in popular CAE software packages.
Useful References

Useful References (cont’d)

Useful References (cont’d)

- Ravi K. Varanasi1, Charles P. Baylis II, Lawrence P. Dunleavy, William Clausen, “Prediction of Harmonic Tuning Performance in pHEMTs,” *IEEE Wireless and Microwave Technology Conference (WAMICON 2005)*, April 7-8, 2005, Clearwater Beach, FL
Useful References (cont’d)

Useful References (cont’d)

- J. Verspecht, “Everything you’ve always wanted to know about hot-s22 (but we’re afraid to ask),” in Workshop at the International Microwave Symposium, June 2002.
Useful References (cont’d)


